ALTERNATIVE AND FUTURE FUELS AND THEIR INFLUENCE ON EMISSIONS FROM ON-ROAD VEHICLES[1]

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Approximately 48% of worldwide oil demand in 1996 was for transportation, and this share is projected to increase to 56% by 2020. Road vehicles consumed about 70% of total transportation energy in 1996, followed next by aircraft at 12%, and other modes of travel. Emissions from transportation sources contribute to air quality concerns, particularly in urban areas, and can have adverse health and environmental impacts, as well as contribute to global warming.

An APEC study is presently underway to compile data on transportation fuels and emissions and to identify potential fuel/vehicle options for reducing emissions from the transportation sector through the use of higher quality petroleum fuels or alternative fuels. This paper gives an update on the status of data collection and analysis for this study. Also included are the results for passenger cars and heavy-duty trucks from a similar study of future petroleum and alternative fuels undertaken in Canada. Fuel/vehicle options for achieving substantial reductions in the emissions of criteria and greenhouse gas emissions from on-road vehicles are identified, and predictions of the emission reductions in 2010 are reported for the most promising scenarios.

INTRODUCTION

According to the US Energy Information Administration (EIA) in 1999, worldwide oil consumption is projected to increase from 71.5 million barrels per day (mmb/d) in 1996 to approximately 110.1 mmb/d in 2020; this is equivalent to an annual growth rate of 1.8%. Oil refined into transportation fuels is forecast to grow at a rate of 2.4% annually over this same period, increasing from 34.6 mmb/d in 1996 to about 61.3 mmb/d in 2020. Oil consumption for transportation fuels is projected to surpass all other uses after 2011 and comprise 56% of total oil consumption by 2020, compared to a 48% share in 1996.

Figure 1 summarizes regional distribution of the 34.6 mmb/d of oil used worldwide for transportation in 1996, as reported by the US EIA (1999). The regional distribution indicates about 40.2% is consumed in North America, 5.8% in Central and South America, 13.9% in developing Asia, 7.2% in Japan and Australasia, and 3.8% in the former Soviet Union, for a total of 70.8%. Projected growth rates in transportation vary widely, depending on the state of development of the transportation infrastructure and the number of motor vehicles. Annual growth rates in transportation-energy demand for the 1996-2020 period are projected to be 1.7% in the United States, 1.3% in Canada, 1.1% in industrialized Asia, 4.2% in developing Asia and 4.2% in Central and South America.

The dominant user of energy in the transportation sector is on-road vehicles. Road vehicles consumed about 74% of all transportation energy in 1996, followed by aircraft at 12%, and other modes of travel. Gasoline is the predominant fuel used for transportation,

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amounting to 47.7% of the total volume of oil consumed worldwide, followed by diesel fuel at 29.5%, jet fuel at 11.6%, residual fuel at 6.9% and other fuels in the balance.
The Expert's Group for Clean Fossil Energy retained Levelton Engineering Ltd. to study the role petroleum fuels and alternative fuels could take in reducing emissions from combustion of transportation fuels. This paper summarizes the objectives, questionnaire development, and data gathering completed to date for this study.
In 1999, Levelton Engineering and co-workers from Natural Resources Canada completed a comprehensive study of petroleum and alternative fuels for passenger cars, heavy-duty trucks and public transit buses. . The study estimated the reduction in greenhouse gas emissions and changes in criteria emissions that could potentially be achieved by utilization of higher quality petroleum fuels or various alternative fuels and vehicles, and the cost effectiveness of these fuel/vehicle options. This paper presents a summary of the findings from this study that pertain to emissions of criteria and greenhouse gases from passenger cars and heavy-duty diesel trucks.

APEC TRANSPORTATION FUELS STUDY (Energy Working Group, 4/99)
The APEC study was initiated in September 1999 and focuses on fuels used by the transportation sectors in all APEC economies. The general objectives of this project are:
- To investigate and document current and forecast transportation energy use, vehicle efficiency and emissions;
- Using the data available for APEC economies, to identify potential options for reducing emissions and improving air quality through use of higher quality or reformulated petroleum fuels or alternative fuels; and,
- To assess the reduction in emissions of criteria[2] and greenhouse gases that could be achieved by future fuel/vehicle options.

<u>Preparation and Distribution of Study Data Questionnaire</u>
The study team designed a questionnaire in consultation with the project steering committee to collect data for the study. The questionnaire consists of five worksheets in a Microsoft Excel™ file requesting the following information:
- Transportation Energy Demand requests current and forecast energy demand by mode of travel; the data is needed for each economy to quantify on a consistent basis the principal energy use subsectors and fuels used.
- Vehicle and Fuel Economy Data for a Representative Urban Area requests data on the number of vehicles, typical vehicle speeds, vehicle age distribution, and gasoline passenger car emission standards.
- Fuel Parameters and Prices requests data on the current and future quality parameters for gasoline and diesel fuel, and the range of typical fuel prices.
- Fuel Resources and Barriers requests qualitative information on the energy resources utilized to meet energy demand and the respondents rating of potential barriers to use of reformulated or alternative fuels.

[2] CO, NOx, VOC, SOx and particulate matter

- National Emissions - requests data on the magnitude of emissions of criteria pollutants and CO_2 from transportation, energy production and “other” source sectors.

Contact names for distribution of the questionnaire were developed using a database made available by the East-West Center in Honolulu, Hawai‘i; the database contains names and contact information for many individuals in government energy and environment agencies in all APEC economies. A distribution list was created from this database and used to distribute the initial batch of questionnaires between November 19 and November 26, 1999 by e-mail, fax and mail. The initial distribution list included 133 individuals from all APEC economies. Subsequently, the questionnaire was distributed to EWG officials and to additional contacts on updated lists of the Expert’s Group for Clean Fossil Energy. . The current list used for tracking the survey includes 177 individuals who have received the questionnaire. Others have been contacted for information as well, bringing the total number approached for information to about 200.

Status of Data Collection

Table 1 summarizes the responses received from APEC economies as of the end of February 2000.

Complete or fairly complete data has been provided or assembled from respondents and other sources from the following economies: Australia, Canada, Malaysia, Mexico, New Zealand, Peru, and the Philippines. Partial data has been received for Hong Kong China, Singapore and Thailand. No data has been received from contacts in Brunei, Chile, China, Indonesia, Japan, Korea, Papua New Guinea, , Russia, Chinese Taipei, the United States, or Vietnam. A limited amount of data on vehicle statistics and energy use in China has been downloaded from government web pages to fill data gaps. Similarly, data available on the web page for the US EIA and the Environmental Protection Agency (EPA) are being reviewed and will fill some of the gaps in basic data for that economy. A response from the United States is needed to properly complete the study.

A member of the project team based in Kuala Lumpur is following up with people in Malaysia, Singapore, Indonesia and Thailand to fill data gaps. This follow-up has generated additional data for Malaysia and Singapore, and more data is expected. Data also are expected from the follow-up with contacts in Indonesia and Thailand.

Data gathering will continue through March 2000 to try and fill the remaining gaps in data. This will improve the results from the study and broaden the applicability of the findings. The 7th APEC Technical Seminar and the 6th Coal Flow Seminar will be attended to contact individuals who may be able to provide additional data for the study.

CANADIAN STUDY OF ALTERNATIVE AND FUTURE FUELS FOR ROAD VEHICLES

Background

As part of a national response to climate change in Canada, a series of Issue Tables were established for key source sectors that guided and coordinated technical analysis and formulation of potential mitigation strategies. The Transportation Issue Table commissioned numerous studies in 1999 to provide background data and develop proposed strategies to reduce greenhouse gas emissions from the transportation sector. Levelton Engineering lead a study team that investigated the role that alternative and future petroleum fuels could play in reducing greenhouse gas emissions from on-road vehicles, focusing on passenger cars, heavy-duty diesel trucks and city transit buses (Levelton, 1999). The study included a review of alternative and future petroleum fuel technology and costs, a review of alternative vehicle technologies for these fuels, calculation of fuel-cycle greenhouse- and non-greenhouse-gas emissions for the fuels of greatest interest, and predictions of the cost effectiveness of reductions in greenhouse gas emissions. The cost effectiveness values determined in the study considered the effects of differential prices in fuels and vehicles, but excluded taxes. Fuels were presumed to be provided by commercial-scale production facilities, while alternative vehicles were presumed to be produced in commercial quantities (20,000 units/year).

Fuel and Vehicle Options Studied

Fourteen potential and future fuels for light-duty vehicles, as well as the effects of oxygenates and detergents for petroleum based fuels, were studied. The fuels were paired to appropriate current and alternative vehicle technologies, leading to nineteen fuel/vehicle combinations that were analyzed in detail to predict greenhouse- and non-greenhouse-gas emissions from passenger cars. The study also analyzed six fuel/engine options for heavy-duty diesel trucks and nine fuel/engine options for city transit buses. Following a review of the technologies for current and possible future fuels and vehicles, the following options were selected for more detailed analysis for passenger cars, heavy-duty trucks and city buses:

Passenger Cars

- Current and Future Petroleum Fuels:
  - Gasoline: 300 ppm S; 30 ppm S; 1 ppm S
  - Diesel: 40 cetane & 500 ppm S; 50 cetane & 50 ppm S
- Alternative fuels:
  - Liquified petroleum gases (e.g. propane)
  - Compressed and liquified natural gas
  - Methanol from natural gas
  - E10 Ethanol from grain in 30 ppm S gasoline
  - E10 & E85 Ethanol from cellulose in 30 ppm S gasoline
  - Hydrogen
  - Electricity

Heavy-duty Trucks

- Diesel: 40 cetane & 300 ppm S; 50 cetane & 50 ppm S
  - Liquified natural gas
  - Liquified petroleum gases (e.g. propane)
  - Biodiesel from canola
  - Dimethyl ether

City Transit Buses

- Diesel: 40 cetane & 300 ppm S; 50 cetane & 50 ppm S
- Compressed natural gas
- Methanol (for fuel cells)
- Biodiesel from canola
- Hydrogen from natural gas or electricity (for fuel cells)
- Dimethyl ether

The current nominal sulfur content of gasoline and diesel fuel in Canada is 300 ppm, which was set as the baseline for current motor fuels. A Canadian regulation requires that the sulfur content of gasoline be reduced to 30 ppm by 2005, and this level was assumed to remain constant through 2020.

Table 2 summarizes the fuel and vehicle technologies judged to warrant more detailed analysis because of their potential to yield a significant reduction in greenhouse gas emissions, recognizing that the timing of implementation and uncertainty in the results varies with the status of the technology. The model incorporated estimates for the improvements in energy-production technology and engine technology that are likely to occur over the period studied. "No" sulfur gasoline refers to gasoline nominally containing 1 ppm sulfur.

Emission Calculation Model

The study determined emissions from each component of the full fuel cycle, including direct and indirect emissions arising from production, refining and distribution of motor fuels, from vehicle tailpipe exhaust, and from the manufacture of vehicles. An existing full-cycle model developed for the United States and partly adapted for Canada by Delucchi was modified for use in the study to provide emission predictions that more accurately reflect Canadian conditions, and current knowledge of emissions from the energy sector. Current information on production, transportation, distribution and use of alternative and future fuels was used for this purpose. The baseline fuel consumption rates for light and heavy-duty vehicles have a strong influence on fuel cycle emissions. The values used in this study were those forecast in "Energy Outlook 1996 Natural Resources Canada for the years 2000, 2010 and 2020.

As described in Delucchi and Lipman (1996) and in a report by Energy and Environmental Analysis Inc. (1999), Delucchi has updated his full-cycle emission model since it was originally developed in 1993.. The updates focused primarily on including recent data for motor fuel production, processing, distribution and use in the United States, and incorporation of improved algorithms for predicting non-greenhouse-gas emissions from motor vehicles based on the US EPA Mobile 5 emission model. The partial Canadianization of the Delucchi model was completed by Delucchi (1998) for Natural Resources Canada between late 1998 and March 1999.

This partially Canadianized version of the fuel-cycle model was the starting point for the work completed in this study. The model contains the most rigorous full-cycle analysis of both greenhouse- and non-greenhouse gases from alternative motor fuels, and has the advantage of incorporating functional capabilities and some of the data for analysis of Canada. A review of the original model indicated that assumptions affecting the calculations of emissions from alternative fuels needed considerable adaptation and refinement to simulate full-cycle emissions for conventional and alternative fuel in Canada.

The Delucchi model is capable of estimating full-cycle emissions of carbon dioxide, methane, nitrous oxide, nitrogen oxides, carbon monoxide, sulfur oxides, nonmethane organic compounds (also known as VOCs) and total particulate matter from combustion sources. The Delucchi model is also able to analyze emissions from conventionally and alternatively fuelled internal combustion engines for both light-duty and heavy-duty vehicles, but cannot analyze all the fuel/vehicle options of interest for Canada.

Because of improvements in fuel economy that are occurring and will continue to develop from alternative propulsion systems such as hybrid combustion/battery systems and fuel cells, the model was expanded in this study to include these systems as well. The following fuel/vehicle combinations were added to the model to enable analysis of all cases identified as potential high-impact opportunities for reducing greenhouse gas emissions:

- canola methyl ester (based on the existing biodiesel capability) for heavy-duty vehicles;
- ethanol from agricultural residues (straw);
- methanol from natural gas used in a fuel-cell-powered light-duty vehicle and bus (the methanol is assumed to be reformed to produce hydrogen on board the vehicle);
- hydrogen from natural gas or electrolysis used in a fuel-cell-powered light-duty vehicle and bus;
- hybrid gasoline/battery powered light-duty vehicle;
- hybrid diesel/battery powered bus; and,
- dimethyl ether from natural gas for use in heavy-duty vehicles.

Existing capabilities for modeling emissions from heavy-duty vehicles were adapted to enable prediction of fuel cycle emissions from production and use of diesel fuel in light-duty vehicles.

Study Results

The results presented in this paper are estimated for 2010. The study also considered emission forecasts for 2000 and 2020. Approximate emissions for gasoline-fueled passenger cars and heavy-duty diesel trucks for the reference case of 300 ppm sulfur fuels are summarized in Table 3. These results represent the approximate midlife average emissions for the vehicles, and were estimated using the simplified emission model developed by Delucchi, which is based on the emission algorithms included in the US EPA Mobile 5 model. They are average emissions for a vehicle bought in 2010 after accumulation of one half of the vehicle's lifetime mileage (about 122,000 km). The tailpipe emissions apply to US Tier 1 vehicles, and do not reflect the lower Tier 2 vehicle emission standards proposed by the US EPA starting in the 2004 model year.

Figure 2 shows estimated passenger car emissions for total ozone precursors for various fuel/vehicle technologies as a fraction of the emissions for the reference case of a conventional vehicle using 300 ppm S gasoline. Total ozone precursors are calculated as NO_x+VOC+CO/7[3], a metric commonly used by the California Air Resources Board as an indicator of total emissions contributing to ozone formation. Significant reductions in emissions can be achieved with the use of 30 ppm S gasoline in conventional and hybrid engine/battery vehicles. The greatest reduction is projected for future fuel-cell vehicles.

The ratio of particulate emissions for fuel/vehicle options compared to the reference fuel is shown for passenger cars in Figure 3. Particulate emissions from diesel vehicles are higher than from gasoline vehicles in spite of the better fuel economy achieved by diesel

[3] This measure is only used here as an indicator of the contribution to ozone formation; the relative contribution of precursors to ozone formation in a region are site-specific and depend on local meteorological conditions and atmospheric chemistry.

engines. Emission factors, shown both for the vehicle alone and for the full fuel cycle, show that particulate emissions from diesel vehicles compare more favorably to those from gasoline vehicles when viewed on a full-cycle basis.

Table 4 summarizes the percent change in emissions of criteria and greenhouse gases for the more important fuel/vehicle options studied for passenger cars. Changes in emissions are shown relative to a conventional vehicle burning gasoline containing 300 ppm sulfur. Figure 4 summarizes the vehicle-only and full-cycle greenhouse-gas emission ratios for passenger cars, and illustrates the importance for many fuels of evaluating fuel/vehicle options on a full-cycle basis. The greatest reductions in full-cycle greenhouse-gas emissions are forecast to be achieved with electric vehicles, followed by E85 (85% ethanol,15% 30-ppm S gasoline) made from cellulosic feedstocks. Substantial reductions in greenhouse gas emissions are predicted to be achievable with high-efficiency, advanced gasoline vehicles and diesel vehicles, as well as with Compressed Natural Gas (CNG) and Liquified Petroleum Gas (LPG) used in optimized conventional internal combustion engines.

Table 5 presents the projected changes in emissions of criteria and greenhouse gases achievable with future low-sulfur diesel fuel and alternative fuels in heavy-duty diesel trucks. The emission changes are shown relative to emissions generated with 300 ppm S diesel fuel. Ozone precursor emissions decline when switching to LPG, Liquified Natural Gas (LNG) or dimethyl ether, while all of the options considered yield a reduction in particulate emissions. LPG and LNG yield 8% and 4% reductions in full-cycle greenhouse-gas emissions, respectively.

CONCLUSIONS

- Fuel and vehicle technologies are interdependent and should be analyzed as a system.
- Comparison of full-cycle emissions of greenhouse gases is preferable to comparison of emissions from vehicles only, as this correctly ranks the reductions in emissions for many potential fuel/vehicle options; full-cycle and vehicle-only emissions are also significantly different for some criteria pollutants.
- Which fuel/vehicle option proves best for reducing air quality impacts and greenhouse gas emissions depends on regional fuel supplies and costs, current vehicle standards, fleet turn-over, and type of application.
- A number of fuel/vehicle options have the potential to achieve substantial reductions in criteria and greenhouse gas emissions relative to current fuel/vehicle technology.
- Emissions from road vehicles can be reduced by:
  - improved gasoline and diesel quality alone.
  - same or improved gasoline and diesel quality combined with lower vehicle emission standards.
  - existing alternative fuels with current vehicle technology.
  - advanced vehicle technology combined with high quality fuels
- Emissions from gasoline vehicles can be reduced by lowering the content of sulfur, RVP, aromatics and olefins, and by increasing the oxygenate content of the fuel; phase-out of lead is another key factor for reducing emissions of particulate matter and air toxics.

- Emissions can be reduced for diesel vehicles by reducing sulfur content and increasing cetane number.
- Emissions from passenger cars generally decrease progressively in the following nominal order:
  - lower vehicle exhaust standards combined with adequate fleet turn-over to introduce these new vehicles reasonably quickly into the fleet.
  - reformulated gasoline and diesel combined with modern pollution control systems on the motor vehicle.
  - The latest vehicle technologies (i.e. hybrid or direct injection engines) enabled by high quality gasoline and diesel.
  - LPG, LNG and CNG.
  - advanced fuel-cell vehicles for hydrogen and methanol.

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Figure 1
Regional Distribution of World Transportation Energy Consumption in 1996
Total = 34.6 mmbd

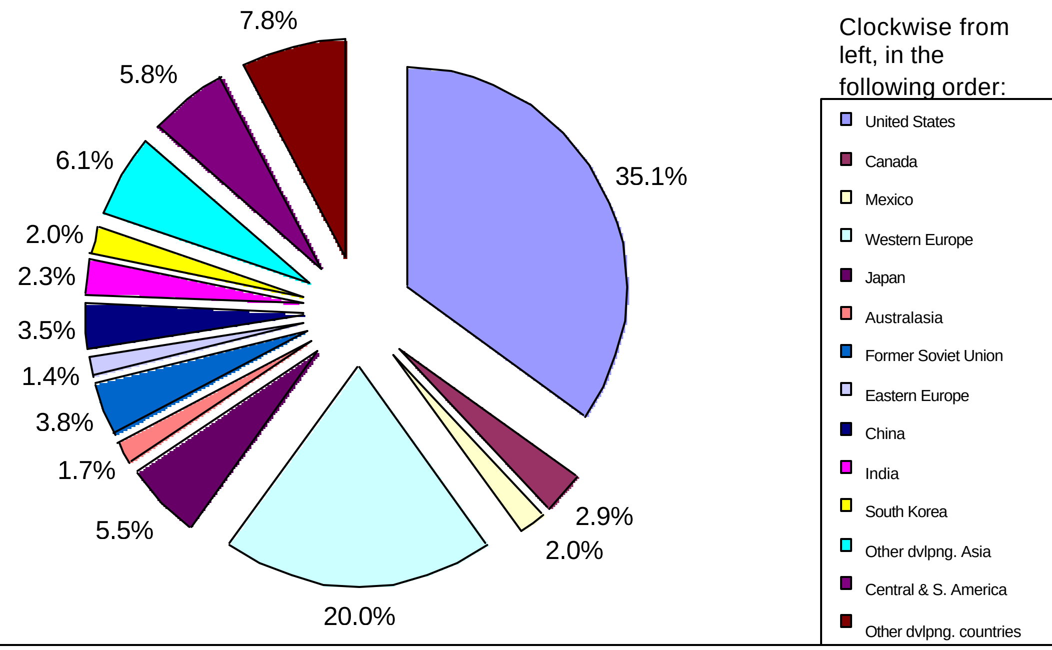

Table 1. Data Responses from APEC Economies as of the End of February, 2000

Economy	Transportation Energy Demand #1	Vehicle Fuel Economy #2	Fuel Parameters #3	Fuel Resources & Barriers #4	National Emissions #5	Date Received
Australia	✓	✓	✓	Partial	✓	Feb 8, 17,21
Brunei Darussalam						No response
Canada	✓	✓	✓	✓	✓	Feb 17/2000
Chile						No response
People's Republic of China	Parital	Partial	No data	No data	No data	No response; Data from web site
Hong Kong, China	Partial	No data	✓	No data	✓	Jan 5
Indonesia						No response
Japan						No response
Republic of Korea						No response
Malaysia	Partial	Partial	✓	✓	Partial	Jan 5
Mexico	✓	No data	✓	✓	Partial	Jan 19
Papua New Guinea						No response
New Zealand	✓	✓	✓	Partial	No data	Dec 23
Peru	✓	Partial	✓	✓	Partial	Jan 31
Philippines	Partial	✓	✓	✓	No data	Jan 24
Russia						No response
Singapore	No data	✓	✓	No data	No data	Jan 4; Feb
Chinese Taipei						No response
Thailand	No data	Very Limited	Partial	Partial	No data	Feb 9
USA						No response
Vietnam						No response

Note: The symbol ✓ indicates that the data has been received and is complete or as complete as possible.

Table 2. Fuel and Vehicle Options for Reducing Emissions

Fuel Technologies	Conventional spark ignition	Direct injection spark ignition	Conventional compression ignition	Advanced compression ignition	Fuel Cell	Electric	Hybrid Engine & Battery	Hybrid Fuel Cell & Battery
Conventional gasoline	**LD**						**LD**	
Low Sulphur gasoline	**LD**	**LD**					**LD**	
"No" Sulphur gasoline		**LD**			**LD, HD**			
Conventional diesel			**LD, HD**				**LD, HD**	
Higher Cetane diesel			**LD, HD**					
Future diesel (1 ppm S)				**LD,HD**				
LPG	**LD**		**HD**					
CNG & LNG	**LD**		**HD**					
Methanol					**LD, HD**			**LD,HD**
Ethanol from grain	**LD**	**LD**						
Ethanol from cellulose	**LD**							
Biodiesel			**HD**					
Hydrogen					**LD,HD**			
Dimethyl ether (DME)			**HD**					
Electricity						**LD,HD**		

Vehicle Technologies

LD - Light Duty Vehicle HD - Heavy Duty Vehicle

Commercial Demonstration Research

Table 3. Emissions in 2010 for Passenger Cars and Heavy-duty Diesel Trucks

Parameter	**Passenger Car (g/km)**	**HD Diesel Truck* (g/km)**
Vehicle CO_2 eq.**	214	1033
Full Cycle CO_2 eq.	298	1331
CO	4.8	10.17
NO_X	0.46	12.77
VOC	0.56	1.68
SO_X	0.06	0.27

* Greater than 3,856 kg gross vehicle weight.

** Sum of CO_2, 21*methane and 310* nitrous oxide.

Figure 2

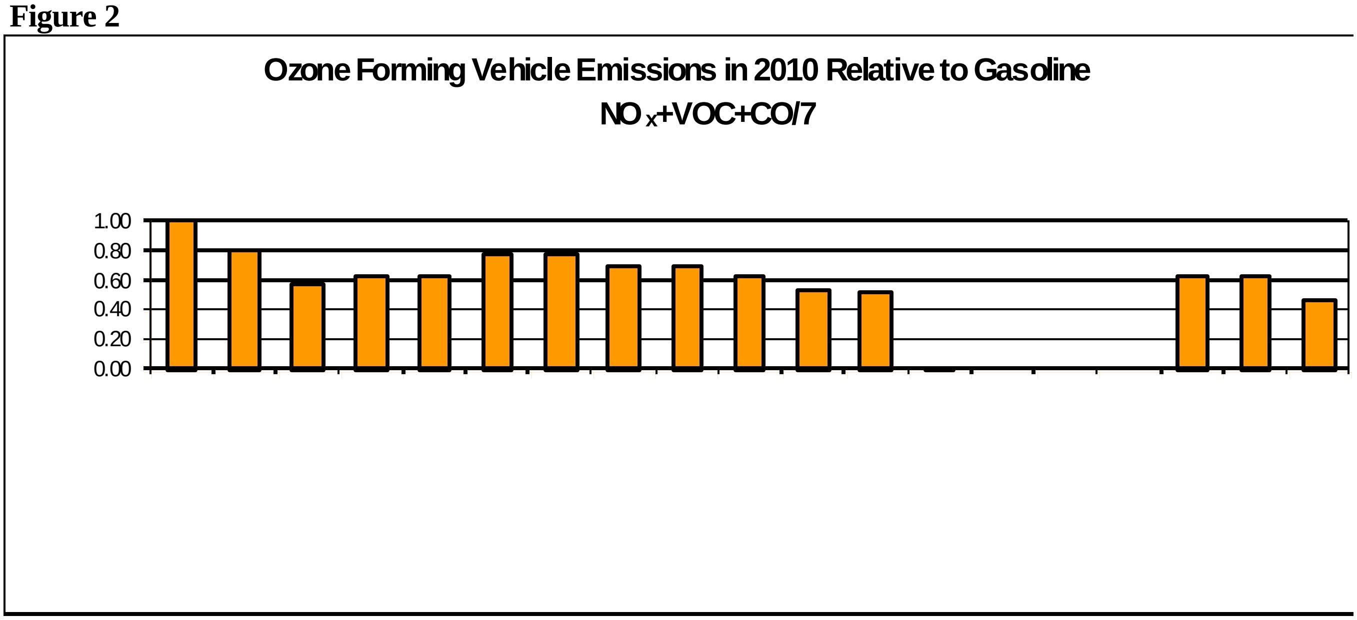

Figure 3

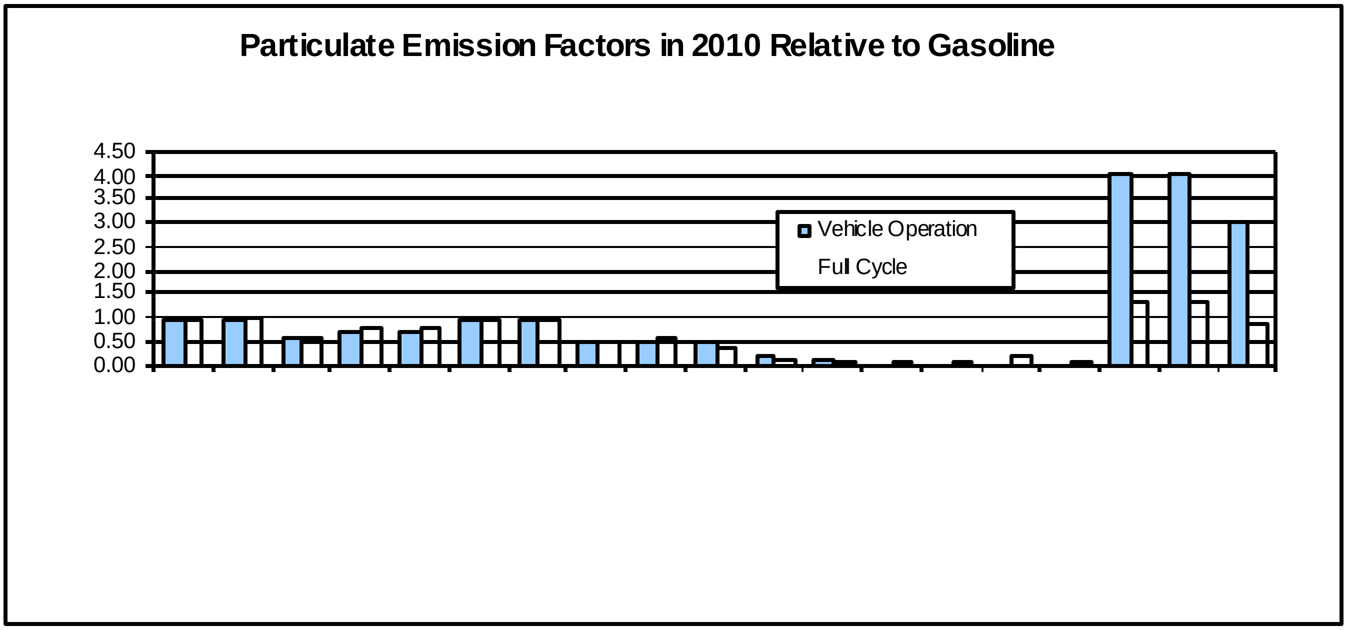

Table 4. Percent Change in g/km Emission Factors for Passenger Cars Relative to Use of 300 ppm S Gasoline

Option	Full Cycle CO_2 Eq.	Vehicle NO_x	Vehicle VOC	Vehicle O_3 Precursors	Vehicle PM
30 ppm S Gasoline	+1	-15	-25	-20	0
30 ppm S Gasoline Hybrid	-35	-41	-42	-41	-41
30 ppm S Gasoline, Direct injection spark ignition	-19	-33	-41	-37	-21
300 ppm S Diesel	-22	+66	-66	-36	+300
50 ppm S Diesel	-21	+66	-66	-36	+300
300 ppm S Diesel Hybrid	-43	+22	-75	-53	+200
LPG	-26	-10	-78	-45	-75
CNG	-25	-10	-92	-49	-80
M100 Fuel Cell	-37	-100	-94	-98	-100
H_2 (NG) Fuel Cell	-52	-100	-100	-100	-100
H_2 (Elect) Fuel Cell	-49	-100	-100	-100	-100
Battery Electric Vehicle	-69	-100	-100	-100	-100
E10 from Corn	-3	-15	-26	-21	-5
E10 from Cellulose	-6	-15	-26	-21	-5

Figure 4

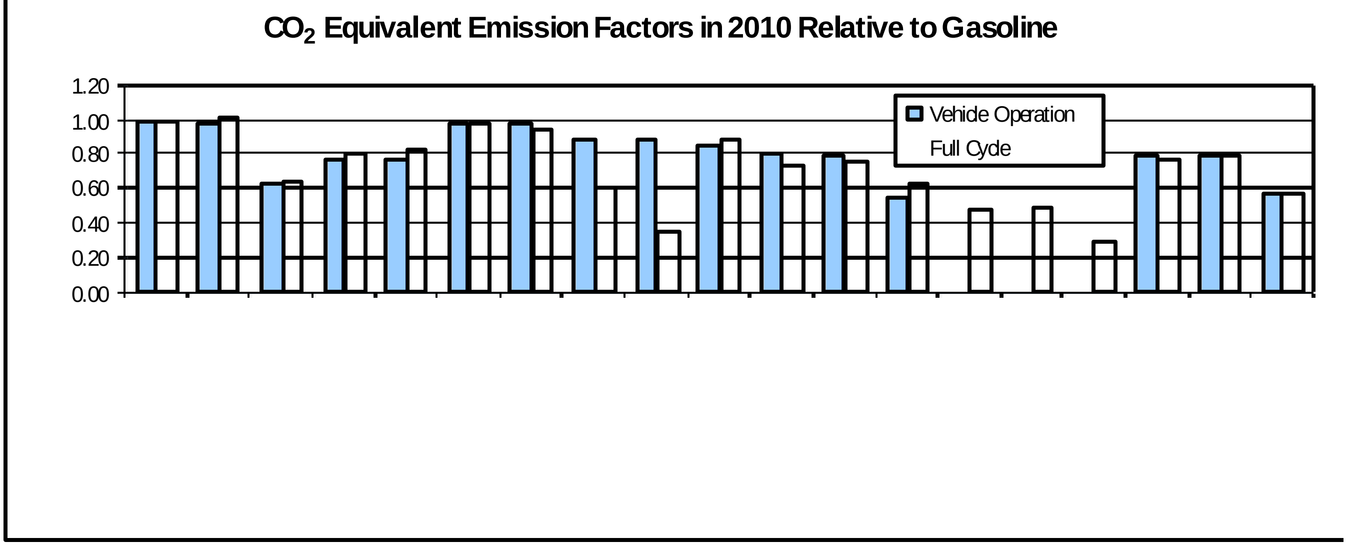

Table 5. Percent Change in Emission Factors for Heavy-duty Diesel Trucks Relative to Use of 300 ppm S Diesel

Option	Full Cycle CO_2 Eq*.	Vehicle NO_x	Vehicle VOC	Vehicle O_3 Precursors	Vehicle PM
50 ppm S Diesel	+1	0	0	0	0
Dimethyl ether	-10	-50	-170	-19	-79
Biodiesel	-51	+30	-80	+9	-50
LPG	-8	-50	+220	-25	-93
LNG	-4	-50	+217	-25	-96

* Sum of CO_2, 21*methane and 310*nitrous oxide.